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ORIGINAL PAPER

Effects of harvesting intensities and techniques on re-growth dynamics and quality of *Terminalia bellerica* fruits in central India

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Abstract: *Terminalia bellerica* Roxb. (Belleric myrobalan) is one of the important multipurpose trees in central India. The fruits of the tree are highly valued for medicinal uses, with the greatest demand coming from the pharmaceutical industry. This has resulted in overexploitation and present harvesting practices have led to a significant decline in natural regeneration for this tree species. Our study was conducted from 2006 to 2009 in Chhattisgarh (India) to standardize suitable harvesting practices for sustainable management for this valuable species. Experiments were conducted at four different sites located in Dhamtari, Sarguja, and Raigarh forest divisions of the state, covering both protected and open forest in a complete randomized block design (RCBD). At each site, linear transects of 200 m × 100 m (2 ha) were randomly selected to sample the initial population and study the effects of two harvesting methods (traditional and nondestructive) and four harvesting intensities (60%, 70%, 80%, and 90%) on the sustainability of *T. bellerica*. Fruits were collected and analyzed for their tannin and gallic acid content. Significant increase in tannin and gallic acid content was found with the maturity of fruits (September to December). This is the first study to experimentally assess the consequences of harvesting of *T. bellerica* fruits in central India. Our findings reveal that harvesting intensity, time, and method are key factors for maintaining the population. Nondestructive harvesting methods were found to be superior to traditional harvesting in terms of regeneration, recruitment, and concentration of active ingredients. When the fruits were harvested through non-destructive means at maturity, the population of species increased. The study concludes that 70% harvest of *T. bellerica* fruits through non-destructive means maintains the sustainability and provides quality raw material for the pharmaceutical industry.

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Introduction

Tropical forests are an important source of nontimber forest products (NTFPs), which play vital roles in traditional livelihoods by providing food security, meeting medicinal needs, and offering sources of income (FAO 1995). At the global level, millions of people dwelling in forests depend on NTFPs for subsistence, income, and livelihood security (Vedeld et al. 2004). Today, with increased market demand, NTFPs are critical source of income and employment generation in many parts of the world. Forexample, *Phytelephas aequatorialis* (Ivory palm) has been in trade for centuries in Ecuador and is currently being marketed internationally with harvesters earning about 40% of their monthly income from Ivory palm collection alone (Runk 1998). Similarly, harvesting different plant parts of *Adansonia digitata* (Baobab tree) provides additional income to rural people in Mali (Gustad et al. 2004).

In India, over 50 million people are directly dependent on NTFPs and about 500 million are indirectly dependent on NTFPs for their sustenance (Tewari 1998). More than 80% of the forest dwellers are dependent on NTFPs for their basic needs, which contribute roughly one-third of their incomes (Government of India 2007). In the state of Madhya Pradesh, about 40%–63% of total rural income comes from the collection and sale of NTFPs (Tewari and Campbell 1996). In Orissa, it is 15%–30%, and the relative contribution is highest amongst the poorest households (Mahapatra and Shackleton 2011).

Increasing commercial demand for the NTFPs has resulted in exploitation, resulting in reduced yields and natural regeneration (Sheldon et al. 1997; Ticktin 2004; Gaoue and Ticktin 2007; Pandey and Mandal 2007). Unsustainable harvesting not only threatens the survival of the tree species, but also the people that depend on them. The promotion of sound and sustainable harvesting practices is vital for many NTFPs, especially those with large and widespread commercial demand beyond the immediate

local population. Management and governance interventions to promote the sustainable use of the trees depend upon what part of the plant is harvested.

The effects of fruit harvesting on population stability are harder to ascertain because of the long-term studies required to detect population trends. This usually requires a modeling approach to determine threshold harvesting levels (Bernel 1998; Emanuel et al. 2005).

A widely commercialized medicinal fruit species in central India is *Terminalia bellerica* (Baheda). *T. bellerica* is used in several Ayurvedic and pharmaceutical preparations: therefore the demand is high, more than 100 tons per year (Ved and Goraya 2007). Harvesting of *T. bellerica* fruits provide vital seasonal-sources of cash income for poor forest dwellers, who harvest the fruit from forest areas, and even declared protected areas. However, there is much concern about the sustainability of the tree species, both in the amount of fruit harvested, as well as the manner in which harvesting takes place (Natesh 2000). *T. bellerica* fruits are currently harvested in a destructive manner by pollarding the branches. Doing so makes harvesting *T. bellerica* fruits far easier than picking individual fruits from the tree. In addition, the harvest starts early in the season, during September and October when the fruits are immature. The results in low-quality produce because the active ingredients responsible for medicinal properties accumulate with maturation. This harvesting method also removes the seed from the forest, thereby reducing the availability of seeds for natural regeneration. As yet, there has been no assessment of the effects of current harvesting approaches on *T. bellerica* fruits in India. Consequently, this study was conducted to assess the effect of fruit harvesting on the natural regeneration and recruitment of *T. bellerica*, and to find suitable methods for sustainable harvesting of *T. bellerica* fruits.

Materials and methods

Species description and uses

Terminalia bellerica Roxb. (family: Combretaceae), commonly known as belleric myrobalan in English and Baheda in Hindi, is an medicinal fruit-bearing tree found throughout Central Asia. It is distributed across the forests of India at an altitude below 10,000 m, except in dry and arid regions. It predominates throughout the plains and low hills in Arunachal Pradesh, Karnataka, Tamilnadu, Chhattisgarh and Madhya Pradesh (Kapoor 1990). The tree is a large deciduous and reaches a height of 50 m and a diameter of 3 m with a rounded crown (Kapoor 1990). The frequently buttressed bole at the base is branchless up to 20 m. The bark is bluish or ashy-grey, covered with numerous fine longitudinal cracks, and the inner bark is yellowish (Wealth of Asia, 1996). The fruits are green and inflated when young and yellowish gray and shrink (nearly seen as ribbed) when mature. Mature fruits become ovoid gray with a stony nut. *T. bellerica* fruit pulp andrind is used by the pharmaceutical industry for making herbal products. It is also good source of gallic acid (3,4,5-trihydroxy benzoic acid) which has antioxidant properties. The fruit also contains extractable high-quality tannin and is used for leather tanning, clothes dyeing and in herbal medicines. The kernel produces non-edible oil, which is used in toilet soap and is good for hair (Wealth of Asia 1996).

T. bellerica fruit is highly valued for its efficacy: a unique property of being both a laxative and an astringent. It has been used to treat various ailments in the indigenous system of medicine (Chopra et al. 1956; Wealth of Asia, 1996), including liver and cardiac disorders.(Nadkarni 1954; Tariq et al. 1977).

The fruit is also reported to have purgative (Chakravarti and Tayal 1947), cardiac depressant, hypotensive and Choleretic effects (Siddiqui 1963). It is one of the constituents of the famous ayurvedic preparation Triphala, which has rejuvenating, astringent, cardioprotective, antacid and antibacterial properties (Wealth of Asia 1996). Experimental studies have also proven this herb as an antidiabetic, antioxidant and antimicrobial (Elizabeth, 2006). A compound isolated from *T. bellerica,* identified as 3,4,5-trihydroxy benzoic acid (gallic acid), was shown to have hepatoprotective activity against carbon tetrachloride (Anand et al. 1997).

Study sites

The state of Chhattisgarh,—lying between 17°46' N to 24°8' N; 80°15' E to 84°51' E has about 44% of its geographical area (135,224 km^2) under forest cover and provides catchments to three river systems (Mahanadi, Godavari, and Indravati). Raipur is the state capital, which is about 1,200 km (south east) away fromIndia's capital, New Delhi. The population of the state is 25.5 million, with agriculture as the major occupation. The temperature ranges from 5–46°C. Rainfall in Chhattisgarh occurs mainly during monsoon season (July to September) with an average annual rainfall of between 1,200 mm–1,500 mm.

The state has the following types of soil: clay, sandy loam, clayey loam, and laterite. However, for the state as a whole, red and yellow loamy soil is predominant. The state is divided into three agro-climatic zones, namely the Bastar Plateau, Northern hilly region, and plains of Chhattisgarh (CGMFP Federation Survey Report 2006). The study sites were located in three forest divisions of the state namely Dhamtari, South Sarguja, and Raigarh to study the effect of harvesting intensities, methods and time on regeneration and recruitment of the species (Table 1). The study sites include two different forest areas viz. peoples protected areas (PPA) and open forest.

The PPA philosophy promotes a proactive, people-friendly, and participatory approach to ensure long-term protection and maintenance of biological diversity while simultaneously providing a sustainable supply of natural products and services to meet local community needs. The minimum forest area for a PPA is 5,000 ha, which local people effectively protect against deleterious impacts such as fire, and overgrazing. In contrast to the PPAs, open forests are the multiple-use, natural forest areas with few limitations or controls on anthropogenic activities.

Table 1. Information about study sites

Location	Latitude	Longitude	Temperature Range (°C)	Mean annual rainfall (mm)
South Singhpur, Dhamtari	20° 48' N	81° 87' E	9-41	1,295
Hariharpur, Kudargarh, South Sarguja	23° 43' N	83° 42' E	5-46	1,500
Mohanpur, Raigarh	22° 42' N	82° 55' E	11-46	1,584

Experimental layout

Harvesting method and intensity

The surveys were conducted during September-October 2006 to select populations of varying density of *T. bellerica*. Experiments were laid out at four sites, namely (i) Singhpur, Dhamtari (PPA) (ii) Singhpur, Dhamtari (open forest) (iii) Kudergarh, South Sarguja (PPA) and (iv) Mohanpur, Raigarh (PPA). At each site, three replicate plots of 200 m × 100 m (2 ha) were randomly selected and within each plot, eight subplots of 50 m × 50 m (0.25 ha) were delineated.

Subplots were first surveyed to quantify the initial population of *T. bellerica* (including seedlings, saplings and trees) in 2006. All individuals in each subplot were counted and tagged as seedlings, saplings, and trees. The subplots were resurveyed annually in December in 2007, 2008, and 2009. Regeneration was recorded for the first two years and recruitment for the last two years. Seedlings (up to 50 cm height) were considered to represent regeneration, whereas saplings (50 cm to 2 m height) represented recruitment. Regeneration was determined by counting new seedling in the sample plots, whereas the annual recruitment rate was calculated using the formula given by Hall *et al*. (1998):

Annual recruitment in percent

$$R = \ln \frac{\left[\left(No - Nd + Nt\right)/\left(No - Nd\right)\right]}{t} \times 100$$

where, *N*t is newly recruited plants in t years, *N*o is the initial number of plants, *N*d is the number of dead plants in t years, t = time

Two harvesting methods were considered, namely the traditional method of collecting immature fruit by branch cutting and the test approach, nondestructive harvesting. In this method, the mature fruits were harvested by vigorously shaking the fruited branches with bamboo poles and collecting the fallen fruit. (To avoid any microbial contamination, polythene sheeting was placed on the ground prior to harvesting.) Simultaneously, four harvesting intensities were applied: 60%, 70%, 80% and 90%. Therefore, there were eight treatments within each plot at every site.

Harvesting time and fruit quality

To find out optimum harvesting time, *T. bellerica* fruits were harvested in five different months i.e. September, October, November, December and January each year. One hundred fruits per tree were collected monthly from all fruited trees from each subplot. All the fruits were bulked and then one hundred fruits were drawn for analysis. The fruits were cleaned, weighed, and dried in the shade at room temperature. To evaluate the quality of the fruits, tannins and gallic acid were determined using spectrophotometer and high-performance liquid chromatography (HPLC), respectively (Schanderi 1970; Choudhary et al. 2007).

Estimation of tannins

Dried *T. bellerica* fruits were powdered in grinding mill. Half a gram of powder was taken in a 250-mL conical flask and 75 mL distilled water was added in it. The flask was gently heated and then boiled for 30 minutes. The solution was centrifuged at 2,000 rpm for 20 minutes and filtered. The supernatant liquid was collected in 100 mL volumetric flask and the volume was made up to 100 mL. One milliliter of the above aliquot was transferred to a 100 mL volumetric flask, containing 75 mL distilled water. To this, 5 mL of Folin-Denis reagent and 10 mL of 35% sodium carbonate solution were added and diluted to 100 ml with distilled water. The solution was shaken well and the absorbance was read at 700 nm after 30 minutes using water as blank solution. A standard graph was prepared by using 0–100 μg tannic acid. The tannin content of the samples as tannic-acid equivalents was calculated from the standard graph.

Estimation of gallic acid

Preparation and extraction of samples

Five grams of dried powdered material was transferred to a conical flask containing 100 mL of 2N hydrochloric acid (HCL). The contents were heated for 30 minutes over a boiling water bath and thencooled and filtered. The filtrate was transferred to a separating funnel and extracted with 150 mL (50 mL × 3) of ether. The combined ether layer was washed with distilled water and dried over anhydrous sodium sulphate, then filtered and evaporated under reduced pressure. The residue thus obtained was dissolved in 10 mL of HPLC grade methanol and kept under refrigeration and used for HPLC. Gallic acid was used as standard to make the calibration curve.

Chromatographic equipment and conditions

A Waters (Milford, USA) gradient HPLC instrument, equipped with two 515 pumps and controlled by an interface module PC2, manual injector valve (Rheodyne), C18 (100 × 4.6 mm i.d.) X bridge HPLC column (Waters, Milford, USA) and Waters 2996 PDA (Photo Diode Array) detector, was used for HPLC analysis. Waters Empower software was used to control the equipment and for the analysis of data. The other operating conditions were: mobile phase- methanol, water and acetic acid (25:75:0.4), flow rate- 1 mL/m, injection volume of 20 μL and detection at 254 nm.

Statistical analysis

The data pertaining to annual regeneration and recruitment rates with respect to harvesting methods and intensities, and data on

the effect of which harvesting month on the quality of *T. bellerica* fruits were subjected to multivariate analysis of variance (MANOVA) using SPSS (Statistical Package for the Social Sciences, Version 14.0) at $p < 0.05$ level of significance. For analysis of regeneration and recruitment, the location, harvesting method, and harvesting intensities were independent variables, whereas values of regeneration and recruitment rate were dependent variables. Moreover, the location and harvesting time were independent variables and values of tannins and gallic acid content were dependent variables. The effect of harvesting methods and intensities on regeneration and recruitment rates were compared using Kruskal Wallis test.

Results

Harvesting method and intensity

The results indicated that the number of *T. bellerica* individuals ranged from 36–112 plants per ha, including seedlings, saplings, and trees (however, number of trees were less) (Table 2). The density of plants was found to be lower in open forest as compared to people protected forest (PPA). The maximum density of *T. bellerica* was found in Hariharpur, Kudurgarh, South Sarguja (PPA), while the minimum density was located in open forest in South Singhpur, Dhamtari. Nondestructive harvesting resulted in the highest regeneration, 4.67±0.94% at South Singhpur, Dhamtari (PPA) in year 2007 and 2.81±0.67% at Mohanpur, Raigarh (PPA) in 2008, compared with the destructive method. Annual recruitment was also found to be higher in sites with nondestructive harvesting coupled with 70% harvesting intensity, 4.15±1.42% at South Singhpur, Dhamtari (PPA) in year 2008 and 2.29±0.13% at Mohanpur, Raigarh (PPA) in 2009. The annual regeneration and recruitment rate varied significantly in open forest and at the South Singhpur, Dhamtari (PPA) site. Recruitment was low in the unprotected forest (open forest) with only 1.2% increase in initial density of plants during the study period, compared to 3.6% increment in the protected forest (Table 2).

Table 2. Regeneration and annual recruitment status of *Terminalia bellerica*

Location	Harvesting method	Harvesting intensity (%)	Initial no. of plants in 2006	Regeneration (%) 2007	Regeneration (%) 2008	Recruitment (%) 2008	Recruitment (%) 2009
South Singhpur, Dhamtari (Open forest)	Traditional	60	10.3±0.09	0.54±0.04^{b}	0.71±0.40^{b}	0.56±0.05^{b}	0.56±0.07^{b}
		70	9.5±0.11	0.94±0.30^{a}	1.01±0.16^{a}	0.75±0.15^{a}	0.98±0.11^{a}
		80	8.8±0.02	0.75±0.06^{b}	0.61±0.27^{b}	0.46±0.03^{b}	0.60±0.08^{b}
		90	10.7±0.11	0.64±0.09^{b}	0.45±0.04^{b}	0.40±0.02^{b}	0.41±0.06^{b}
	Non-destructive	60	13.0±0.13	0.98±0.12^{b}	0.57±0.04^{b}	0.85±0.05^{b}	0.94±0.17^{b}
		70	10.5±0.13	1.17±0.14^{a}	1.61±0.17^{a}	1.94±0.08^{a}	1.86±0.14^{a}
		80	9.7±0.10	0.85±0.11^{b}	0.54±0.13^{b}	0.53±0.18^{b}	0.88±0.11^{b}
		90	10.5±0.11	0.71±0.09^{c}	0.43±0.05^{c}	0.50±0.02^{b}	0.65±0.09^{b}
South Singhpur, Dhamtari (PPA)	Traditional	60	12.3±0.12	1.19±0.04^{a}	1.01±0.02^{a}	1.16±0.05^{a}	0.24±0.02^{a}
		70	16.5±0.29	1.75±0.06^{a}	0.94±0.01^{ab}	1.46±0.03^{a}	0.64±0.03^{a}
		80	19.8±0.16	1.44±0.30^{a}	0.91±0.02^{ab}	1.19±0.05^{a}	0.12±0.01^{a}
		90	14.7±0.14	1.14±0.09^{a}	0.62±0.04^{a}	0.68±0.02^{a}	0.21±0.02^{a}
	Non-destructive	60	20.0±0.15	3.37±0.32^{b}	1.73±0.21^{a}	3.64±0.77^{ab}	0.80±0.17^{a}
		70	12.5±0.21	4.67±0.94^{a}	1.85±0.03^{a}	4.15±1.42^{a}	0.87±0.02^{a}
		80	15.4±0.15	3.09±0.11^{b}	1.11±0.08^{b}	2.18±0.76^{b}	0.53±0.06^{b}
		90	20.5±0.15	3.00±0.41^{b}	1.04±0.05^{b}	2.74±0.19^{ab}	0.80±0.07^{a}
Hariharpur Kudurgarh, South Sarguja (PPA)	Traditional	60	15.6±0.21	0.75±0.04^{b}	0.38±0.01^{a}	0.65±0.01^{a}	0.11±0.02^{a}
		70	24.4±0.17	1.99±0.01^{a}	0.78±0.01^{a}	0.93±0.03^{a}	0.17±0.01^{a}
		80	19.8±0.17	0.71±0.02^{b}	0.69±0.05^{a}	0.64±0.01^{a}	0.09±0.01^{a}
		90	25.7±0.24	0.61±0.03^{b}	0.45±0.02^{a}	0.60±0.02^{a}	0.09±0.01^{a}
	Non-destructive	60	27.7±0.28	1.96±0.02^{ab}	1.10±0.02^{ab}	1.79±0.15^{b}	0.47±0.28^{ab}
		70	28.3±0.29	2.29±0.56^{b}	1.38±0.16^{a}	2.78±0.16^{a}	0.62±0.09^{ab}
		80	26.4±0.18	1.79±0.86^{ab}	1.12±0.03^{a}	1.53±0.36^{b}	0.55±0.08^{a}
		90	17.2±0.23	1.50±0.02^{a}	1.14±0.09^{a}	1.72±0.21^{b}	0.55±0.35^{a}
Mohanpur, Raigarh (PPA)	Traditional	60	17.9±0.13	0.85±0.04^{b}	0.38±0.09^{a}	1.47±0.02^{a}	0.77±0.17^{b}
		70	25.4±0.17	1.39±0.05^{a}	0.83±0.02^{a}	1.57±0.02^{a}	1.60±0.24^{a}
		80	16.9±0.27	0.75±0.03^{b}	0.34±0.23^{a}	0.69±0.04^{b}	0.57±0.26^{b}
		90	27.7±0.29	0.53±0.02^{b}	0.23±0.03^{a}	0.56±0.02^{b}	0.61±0.21^{b}
	Non-destructive	60	17.5±0.22	2.32±0.16^{b}	0.90±0.34^{b}	2.18±0.14^{b}	2.01±0.05^{a}
		70	21.3±0.34	3.41±0.03^{a}	2.81±0.67^{a}	3.30±0.25^{a}	2.29±0.13^{a}
		80	24.6±0.27	2.01±0.02^{b}	0.88±0.35^{b}	1.88±0.80^{b}	1.23±0.03^{a}
		90	24.4±0.21	1.67±0.25^{b}	1.50±0.20^{b}	1.58±0.42^{b}	1.59±0.09^{a}

Mean values within each column followed by different letters differ significantly at $p<0.05$.

Harvesting intensity significantly influenced regeneration (F =6.78, $p \leq 0.000$) and recruitment (F = 2.35, p =0.111) rates (Table 3) among all the studied sites. The interaction effect of harvesting intensity with year on regeneration and recruitment was not significantly different. For most sites and years, non-destructive harvesting was better than the traditional method with respect to regeneration (χ^2 =6.179; p =0.103) and recruitment (χ^2 =3.564; p =0.313). Statistically, non-destructive harvesting of 70% fruits was found to be the best treatment as determined by the Duncan Multiple Range Test (DMRT).

Table 3. Results of general linear model to test the effect of fruit harvesting treatments and year on regeneration and recruitment of *T. bellerica*

Effect	Regeneration				Recruitment			
	SS	df	MS	F value	SS	df	MS	F value
Between subject effects								
Corrected model	8.23	7	1.17	5.52	15.62	7	2.23	26.50*
Treatment	1.5	3	0.5	6.78*	1.15	3	0.38	2.35
Years	5.42	1	5.42	25.43*	12.76	1	12.76	151.56*
Treatment × Years	1.31	3	0.44	2.06	1.71	3	0.57	6.78*
Error	3.41	16	0.21		1.35	16	0.08	

Regeneration R^2 =0.707, Recruitment R^2 =0.921, SS =Sum of square, MS =mean square, DF =degree of freedom. * significant at p <0.000

Table 4. Tannins and gallic acid content in *T. bellerica* fruits harvested at different months of the fruiting season

Location	Harvesting time	Tannins (%)	Gallic acid ($mg \cdot g^{-1}$)
South Singhpur, Dhamtari (Open Forest)	September	8.21±0.31^{b}	15.08±0.19^{bc}
	October	9.65±0.25^{b}	17.29±0.15^{b}
	November	10.69±0.17^{ab}	19.35±0.89^{ab}
	December	11.17±0.31^{a}	21.28±0.67^{a}
	January	10.85±0.21^{ab}	20.27±0.24^{a}
South Singhpur, Dhamtari (PPA)	September	9.54±0.28^{ab}	17.67±0.52^{c}
	October	10.33±0.45^{ab}	19.14±0.55^{bc}
	November	10.07±0.77^{ab}	21.29±2.16^{b}
	December	12.45±0.41^{a}	24.15±0.87^{a}
	January	11.68±0.39^{a}	23.94±0.29^{a}
Hariharpur Kudurgarh, South Sarguja (PPA)	September	8.62±0.15^{b}	15.28±0.34^{c}
	October	9.95±0.81^{b}	17.68±0.93^{c}
	November	11.18±0.44^{ab}	20.50±0.75^{b}
	December	14.04±0.35^{a}	23.04±0.35^{a}
	January	12.69±0.56^{ab}	21.57±0.62^{b}
Mohanpur, Raigarh (PPA)	September	8.27±0.50^{bc}	17.05±0.46^{b}
	October	10.08±0.55^{b}	18.94±0.85^{b}
	November	11.35±0.52^{ab}	19.85±0.33^{b}
	December	13.22±0.91^{a}	23.98±0.92^{a}
	January	12.68±0.37^{a}	22.59±0.37^{a}

Mean values within each column followed by different letters differ significantly at p <0.05.

Tannin and gallic acid content

Significant variation was seen in concentration of tannin and gallic acid during the fruiting season (September to January) at each site. The concentration of both the active ingredients increased with maturity. The concentration of tannin was higher (14.04±0.35%) in December at Hariharpur, Kudergarh, South Sarguja (PPA) site when the fruits were mature and was lower (8.21±0.31%) in September at South Singhpur, Dhamtari (open forest) site when the fruits were immature. Gallic acid concentration was higher (24.15±0.87 $mg.g^{-1}$) in December at South Singhpur, Dhamtari (PPA) and lower (15.08±0.19 $mg.g^{-1}$) in September at South Singhpur, Dhamtari (open forest) (Table 4). Harvesting time (month) has significantly affected the tannins (F=69.102, p=0.000) and gallic acid concentration (F=73.375, p=0.000, Table 5). The percent increase in tannins and gallic acid content ranged from 23.37%–38.60% and 26.83%–33.68% respectively. The experimental sites didn't have any significant influence on tannin and gallic acid content as determined by Duncan's Multiple Range Test (DMRT).

Table 5. Results of general linear model to test the effect of fruit harvesting time, site, and year on tannins and gallic acid concentrations in fruits of *T. bellerica*

Effect	Tannin concentration				Gallic acid concentration			
	SS	DF	MS	F	SS	DF	MS	F
Corrected model	149.661	19	7.877	16.152*	430.343	19	22.65	16.661*
Site	5.757	3	1.919	3.935	11.309	3	3.77	2.773
Month	134.798	4	33.699	69.102*	398.987	4	99.747	73.375*
Site×Month	9.106	12	0.759	1.556	20.048	12	1.671	1.229
Error	19.507	40	0.488		54.376	40	1.359	
Total	7204.683	60			23878.596	60		

Tannin concentration: R^2=0.885, Gallic acid concentration: R^2 =0.888, SS =Sum of square, DF =degree of freedom, MS =mean square, * significant at p <0.000

Discussion

Effect of fruit harvesting methods on regeneration and recruitment of *T. bellerica*

Population density of *T. bellerica* was significantly higher in PPA sites than in open forest sites. Several workers reported that there are many biotic and abiotic factors that affect the population structure (Lykke 1998; Tesfaye et al. 2002; Wadt et al. 2005; Peres et al. 2003; Bhuyan et al. 2003). In the present investigation, populations of *T. bellerica* in open forest have more biotic and abiotic pressure than sites located in PPA areas. Management practices were better in PPA areas because local communities were involved in forest management and there were no evidence of fire and grazing. However, heavy grazing and a few fires were observed in the open forest. The forests located near the human

settlement were under more biotic pressure than the forests located farther away.

Botha et al. (2004) observed that the harvesting intensity of specific plant species often decreased with increasing distance from human settlements. In our investigation, we observed a difference in regeneration and recruitment at regions proximal to the settlements (perhaps due to an increased level of human disturbances). Furthermore, the regeneration and recruitment rates were high in low-intensity harvesting sites but very low in high-intensity harvesting sites. Similarly, Avocevou-Ayisso et al. (2009) reported a significant effect on the regeneration of *Pentadesma butyracea* at low- and high-fruit harvesting intensity sites in Benin.

Populations of *Phyllanthus emblica* and *P. indofischeri* were more sensitive to destructive harvesting (for example, lopping of branches) than to fruit harvesting (Sinha and Bawa 2002). They found that such harvesting techniques reduced fruit production in the following year for these species. Furthermore, Murali and Hegde (1997) suggested that regulated fruit harvest should require leaving some fruits on the tree for regeneration. Bernel (1998) observed that for Tagua (*Phylephus seemanni*) 86% of fruit could be safely harvested without affecting the population, and Emanuel et al. (2005) reported that 92% fruits of *Sclerocarya birrea* could be harvested without impacting the current population in South Africa. However, Guedje et al. (2003) found the population model of *Garcinia lucida* to be relatively insensitive to fruit harvesting.

The results revealed that when sites are destructively over-harvested, they tend to have fewer individuals in different age-classes. The variation in regeneration and recruitment rates at various sites with regard to harvesting methods and intensities could be resulting from over-harvesting. Many workers (Pandey and Shackleton, 2012; Shackleton et al. 2005; Ticktin 2004) indicated that heavy harvesting of fruits and seeds could have long-term detrimental effects on recruitment of new individuals and can bring changes in the population structure and dynamics of plants being harvested due to poor regeneration and recruitment. However, Harper (1977) suggested that to correctly measure the recruitment rate, the study should be conducted over a series of years to eliminate the effect of episodic regeneration. Furthermore, there is some evidence that fruit yield is highly variable from year to year (Shackleton, 2002) and hence it is realistic to expect some fluctuations in recruitment of concerned species.

Harvesting time and quality of fruits

The best time for collection should be according to maturity of fruits as the concentration of biologically active ingredients varies with fruit development and maturity. In the present investigation, the tannin and gallic acid content increased in December when the fruits were mature and decreased in September when the fruits were immature. Cirak et al. (2007) studied variation in bioactive secondary metabolites in *Hypericum origanifolium* during its phenological cycle and reported increase in the concentration of secondary metabolite on fruit maturation. Mhamdi et al. (2010) reported increase in the concentration of total phenolic acids with the ripening of Borage seeds (*Borago officinalis*). Pandey et al., 2005 also reported increase in tannin and gallic acid content in *Phyllanthus embilica* fruits with maturity. The variation in tannins and gallic acid content observed in our study can be attributed to the variation in the harvesting time which influences the quality of *T. bellerica* fruits. The fruits should be harvested after maturity when they change colour from green to dark brown. Harvesting time plays an important role not only in maintaining fruit quality but also on sustainability because only mature fruits produce viable seeds (Pandey and Shackleton, 2012). We recommend that fruit should be harvested during December to mid-January to ensure quality of both source materials and finished products.

Prescription for sustainable harvesting

In our study, we found that mature fruits harvested by nondestructive means (plucking by hand or gathering from the ground) with 70% harvesting limit appear to be sustainable. It is difficult to develop a universal harvesting limit because fruiting varies year to year. Therefore, the amount of fruits to be harvested depends upon the fruiting trees in that particular year. If the fruiting population is more (20 fruited trees per ha) then 5%–10% fruits are enough to maintain sustainability whereas in areas where the population is lower (10 fruited trees per ha) more fruits (20%–30%) should be left to maintain sustainability. If collectors find it difficult to decide the percentage of fruits left for regeneration, they can leave one or two fruited branches per tree at the time of collection.

Conclusion

As the overexploitation and present harvesting approaches are compromising the long-term utilization of *T. bellerica* resources, the ecological and quality assessments of harvesting from wild populations are necessary to evaluate the sustainability of harvest and quality of the product. The study revealed that nondestructive harvesting of 70% of the fruit was the optimum for maintaining sustainability of *T. bellerica*. Mature fruits should be nondestructively harvested in the month of December to get quality raw material for various herbal formulations. Nondestructive harvesting of mature fruits helps in maintaining the population because only mature fruits will produce viable seeds. The study revealed that the annual regeneration and recruitment rates were higher in PPAs in comparison to open forests due to anthropogenic pressure, differences in management practices, and involvement of communities. However, we also note that a more conservative harvesting limit would serve as a buffer against occasional over-harvesting. Moreover, additional work is needed to determine what harvesting levels are sustainable in other habitats.

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